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Research Article

Digital twin simulation to predict orthodontic relapse before treatment completion

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ABSTRACT

Orthodontic relapse remains one of the greatest challenges in achieving long-term treatment stability, often resulting from complex interactions among biological remodeling, biomechanical forces, patient compliance, and retention strategies. Recent advances in digital dentistry have introduced digital twin technology as a transformative approach for creating dynamic, patient-specific virtual models that continuously integrate clinical, imaging, and treatment data throughout orthodontic care. By combining three-dimensional imaging, intraoral scanning, artificial intelligence, biomechanical simulation, and predictive analytics, digital twins enable clinicians to monitor treatment progression in real time and forecast the likelihood of relapse before active treatment is completed. This proactive approach supports individualized treatment planning, optimization of force application, timely modification of therapeutic strategies, and personalized retention protocols to improve long-term outcomes. Digital twin simulation also enhances clinical decision-making by providing visual representations of anticipated tooth movement and treatment responses, thereby facilitating better communication between clinicians and patients. Although challenges related to data integration, computational demands, model validation, interoperability, and ethical management of patient information remain, ongoing developments in artificial intelligence and digital technologies continue to strengthen the feasibility of clinical implementation. Digital twin simulation has the potential to redefine predictive orthodontics by enabling precision-based, adaptive, and preventive treatment strategies that minimize relapse risk while improving treatment efficiency, stability, and patient-centered care.

Introduction

Orthodontic treatment aims to establish functional occlusion, facial harmony, and long-term stability of tooth position. Despite significant advances in orthodontic appliances and treatment protocols, orthodontic relapse remains a persistent clinical challenge that can compromise treatment outcomes after appliance removal. Relapse is influenced by multiple factors, including periodontal ligament remodeling, craniofacial growth, occlusal forces, muscular adaptation, treatment mechanics, and patient compliance with retention protocols. Consequently, there is an increasing need for predictive technologies capable of identifying relapse risk before treatment completion, enabling clinicians to implement timely preventive interventions (Guo & Shao, 2025).

The emergence of digital twin technology represents a paradigm shift in precision orthodontics. A digital twin is a dynamic virtual representation of an

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individual patient that continuously integrates clinical findings, three-dimensional imaging, intraoral scans, cephalometric analyses, biomechanical simulations, and artificial intelligence (AI)-driven predictive models. Unlike conventional digital models that provide static representations, digital twins evolve throughout treatment, allowing real-time monitoring, simulation of tooth movement, and individualized prediction of treatment outcomes (Ma et al., 2024; Amarnath et al., 2025).

The effectiveness of digital twin simulation depends on the integration of high-quality digital datasets. Cone-beam computed tomography (CBCT), digital intraoral scanning, facial imaging, and computer-aided design/computer-aided manufacturing (CAD/CAM) technologies provide detailed anatomical information that supports accurate virtual model construction and biomechanical analysis (Singh, 2018; Patil et al., 2025). Furthermore, advances in explainable AI, reinforcement learning, and adaptive clinical decision-support systems have improved the ability to personalize orthodontic treatment plans while continuously updating predictions based on patient-specific responses (Li & Wang, 2025; Guo & Shao, 2025). Broader developments in AI-assisted surgical planning and digital healthcare further reinforce the growing role of intelligent computational models in craniofacial treatment planning (Sinha & Srivastava, 2025). Although Chandra et al. (2021) focused on biomechanical performance in restorative dentistry, their findings underscore the importance of structural stability and material behavior, principles that are equally relevant when modeling biomechanical responses within digital twin simulations. Digital twin simulation therefore offers a promising framework for predicting orthodontic relapse before treatment completion, supporting proactive treatment modifications, individualized retention strategies, and improved long-term clinical stability.

Foundations of Digital Twin Simulation in Orthodontics

Digital twin simulation in orthodontics is founded on the creation of a dynamic virtual replica of an individual patient's craniofacial structures, dentition, and surrounding tissues that continuously updates using real-time clinical and imaging data. Unlike conventional digital models, a digital twin integrates anatomical, biomechanical, and biological information with artificial intelligence (AI) to predict treatment responses and optimize clinical decision-making (Ma et al., 2024; Amarnath et al., 2025).

The development of an orthodontic digital twin begins with comprehensive data acquisition. Cone-beam computed tomography (CBCT) provides accurate three-dimensional visualization of teeth, alveolar bone, and craniofacial anatomy, while intraoral scanners, facial scanners, digital photographs, and cephalometric records contribute detailed morphological information for constructing patient-specific models (Singh, 2018; Patil et al., 2025). These datasets are integrated within AI-enabled platforms that continuously synchronize virtual and clinical environments.

Advanced machine learning, deep learning, and reinforcement learning algorithms analyze treatment progression, simulate biomechanical responses, and estimate relapse risk by recognizing complex patterns that may not be apparent through conventional assessment. Explainable AI further improves clinician confidence by providing transparent reasoning behind predictive recommendations, supporting personalized orthodontic planning and adaptive treatment modifications (Li & Wang, 2025; Guo & Shao, 2025). The integration of biomechanical simulations with biological remodeling processes enhances prediction accuracy and enables proactive interventions before undesirable tooth movement occurs (Sinha & Srivastava, 2025). Digital twins therefore establish the technological foundation for precision orthodontics by combining multimodal data, predictive analytics, and continuous patient monitoring into a unified clinical framework (Ma et al., 2024).

Digital Twin Simulation for Orthodontic Relapse Prediction

Digital twin simulation creates a continuously updated virtual representation of an individual patient's craniofacial structures, dentition, periodontal tissues, and biomechanical environment to predict orthodontic outcomes, including relapse, before active treatment is completed. By integrating CBCT, intraoral scans, cephalometric records, treatment history, and AI-driven predictive algorithms, the digital twin enables clinicians to evaluate multiple treatment scenarios and identify instability before appliance removal (Ma et al., 2024; Amarnath et al., 2025; Patil et al., 2025).

Biological Basis of Orthodontic Relapse

Orthodontic relapse is influenced by periodontal ligament remodeling, alveolar bone adaptation, soft tissue elasticity, occlusal forces, craniofacial growth, and patient-specific biological responses. Digital twins incorporate these variables into biomechanical models to estimate post-treatment tooth movement and identify teeth at greater risk of relapse, enabling individualized retention planning (Ma et al., 2024; Guo & Shao, 2025).

Virtual Simulation of Tooth Movement

Finite element analysis and biomechanical simulations reproduce the effects of orthodontic forces on teeth,

Table 1: Core Components of an Orthodontic Digital Twin and Their Clinical Functions

Component	*Primary Data Source*	*Clinical Function*	*Contribution to Relapse Prediction*
CBCT Imaging	Three-dimensional radiographs	Skeletal and dental assessment	Predicts bone remodeling and tooth stability (Singh, 2018)
Intraoral Scanning	Digital impressions	Accurate dental arch modeling	Detects positional changes over time
Facial & Cephalometric Records	Photographs and cephalograms	Soft tissue and facial profile evaluation	Correlates esthetic and functional outcomes
AI & Reinforcement Learning	Integrated clinical datasets	Treatment prediction and decision support	Identifies individualized relapse risk (Li & Wang, 2025)
Biomechanical Simulation	Digital twin platform	Force distribution and tooth movement analysis	Optimizes treatment and retention strategies (Ma et al., 2024)

supporting structures, and surrounding bone. High-resolution CBCT and 3D imaging provide anatomical accuracy for these simulations, allowing clinicians to evaluate force distribution, root displacement, and tissue responses before clinical implementation (Singh, 2018; Patil et al., 2025).

AI-Based Risk Assessment

Machine learning, reinforcement learning, and explainable AI continuously analyze treatment progress to estimate relapse probability, recommend force adjustments, and optimize retention strategies. Transparent AI outputs improve clinician confidence and facilitate personalized clinical decision-making (Li & Wang, 2025; Guo & Shao, 2025).

Continuous Treatment Monitoring

Digital twins are dynamically updated with new clinical records, enabling adaptive treatment modifications throughout therapy. This continuous monitoring supports early intervention when unfavorable movement patterns emerge, improving treatment stability and long-term outcomes (Ma et al., 2024; Amarnath et al., 2025; Sinha & Srivastava, 2025).

Although Chandra et al. (2021) primarily investigated structural performance in restorative dentistry, the study highlights the importance of biomechanical behavior and material stability, concepts that underpin predictive biomechanical simulations within digital twin frameworks.

Clinical Applications, Benefits, Challenges, and Future Perspectives

Digital twin simulation is transforming orthodontics by enabling patient-specific virtual replicas that continuously integrate imaging, clinical, and biomechanical data throughout treatment. Clinically, it supports individualized treatment planning, prediction of orthodontic relapse before appliance removal, optimization of tooth movement, assessment of retention requirements, and monitoring of treatment progress through dynamic updates. Integration with CBCT, intraoral scanning, CAD/CAM systems, and AI-driven decision support further enhances diagnostic precision and personalized care (Singh, 2018; Patil et al., 2025; Ma et al., 2024). In complex orthodontic and orthognathic cases, digital twins facilitate interdisciplinary planning and improve treatment predictability (Li & Wang, 2025; Sinha & Srivastava, 2025).

The major benefits include improved prediction of relapse risk, early identification of unfavorable biomechanical responses, reduced treatment uncertainty, enhanced patient communication through virtual simulations, and more individualized retention strategies. Continuous learning from longitudinal patient data allows adaptive treatment modifications, promoting greater efficiency and long-term stability (Guo & Shao, 2025; Amarnath et al., 2025).

Current challenges include the need for standardized

Table 2: Digital Twin Workflow for Orthodontic Relapse Prediction

Stage	*Digital Twin Activity*	*Clinical Contribution*
Data Acquisition	CBCT, intraoral scans, facial records	Accurate patient-specific model
Virtual Simulation	Biomechanical and finite element modeling	Predicts tooth movement and stability
AI Risk Analysis	Machine learning and explainable AI	Estimates relapse risk and retention needs
Dynamic Monitoring	Continuous data synchronization	Enables adaptive treatment modifications
Clinical Decision Support	Personalized treatment recommendations	Improves long-term orthodontic stability

Table 3: Clinical Perspective of Digital Twin Simulation in Orthodontic Relapse Prediction

Aspect	*Clinical Impact*
Applications	Personalized planning, relapse prediction, treatment monitoring, retention optimization
Benefits	Improved accuracy, adaptive treatment, better patient communication, enhanced long-term stability
Challenges	Data integration, computational cost, interoperability, privacy, clinical validation
Future Perspectives	Explainable AI, reinforcement learning, cloud-based digital twins, real-time adaptive orthodontics

data integration, high computational demands, limited interoperability among digital platforms, substantial implementation costs, and concerns regarding data privacy and regulatory compliance. Furthermore, large-scale clinical validation is necessary before routine adoption, while maintaining clinician oversight remains essential for reliable decision-making (Ma et al., 2024; Amarnath et al., 2025). Advances in AI, reinforcement learning, cloud computing, and explainable clinical decision-support systems are expected to further improve predictive accuracy and facilitate widespread clinical implementation (Li & Wang, 2025).

Conclusion

Digital twin simulation represents a significant advancement in orthodontics by shifting treatment strategies from reactive correction to predictive and preventive care. By integrating artificial intelligence, three-dimensional imaging, biomechanical modeling, and continuous patient-specific data analysis, digital twins provide a powerful framework for predicting orthodontic relapse before treatment completion. This technology enables clinicians to identify unfavorable treatment responses early, optimize tooth movement strategies, and develop individualized retention protocols that improve long-term stability. Although challenges related to data standardization, computational requirements, cost, privacy, and clinical validation remain, ongoing developments in AI and digital orthodontic platforms continue to enhance its clinical feasibility. Future integration of explainable AI, reinforcement learning, real-time monitoring systems, and advanced imaging technologies is expected to further improve decision-making accuracy and patient outcomes. Digital twin-based orthodontics has the potential to establish a new paradigm of precision dentistry, where treatment planning, monitoring, and relapse prevention are continuously adapted to each patient's biological and biomechanical characteristics, ultimately improving efficiency, predictability, and quality of care.

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